

THE EFFECTS OF TEMPERATURE AND STRAIN RATE ON
THE YIELDING BEHAVIOR OF THE SINGLE CRYSTAL SUPERALLOY PWA 1480

Walter W. Milligan and Stephen D. Antolovich
Fracture and Fatigue Research Laboratory
School of Materials Engineering
Georgia Institute of Technology
Atlanta, Georgia 30332-0245

Recent advances in precision casting techniques and alloy development have allowed the introduction of directionally solidified and single crystalline turbine blades in aircraft gas turbine engines and advanced rocket engines. Because these alloys exhibit complex anisotropic elastic and plastic properties, the conventional continuum-mechanical approach to constitutive modelling is frequently inadequate. This has led designers and analysts to try to understand fundamental metallurgical deformation and damage mechanisms in these alloys, and to incorporate some of these mechanisms in their models. The goal of this project is to characterize these fundamental mechanisms in the nickel-base superalloy PWA 1480, and to interact with the mechanics-oriented analysts in an attempt to develop physically-based constitutive models for this alloy.

In addition to the anisotropic elastic and plastic properties which are inherent to a single crystal, nickel-base superalloy single crystals also exhibit complex behavior due to their microstructures. The alloys are strengthened by the precipitation of the γ' phase, and this phase is the dominant microstructural feature (about 60 volume % of the alloy). Because γ' is an ordered phase, it shows an anomalous increase in strength with temperature, and also exhibits very complicated orientation-dependent behavior.⁽¹⁾ Because the superalloy is composed of 60% γ' , some of this behavior is also evident in the superalloy. However, it must be stressed that the superalloy is a composite structure, consisting of two phases. It is of the highest importance to determine how dislocations interact with the precipitates and with the matrix/precipitate interfaces during deformation. These interactions are very dependent on temperature, strain rate, and stress state.

The first phase of the project has been completed.⁽²⁾ Interrupted tensile tests were conducted on $\langle 001 \rangle$ oriented single crystals at temperatures from 20-1093°C. Two strain rates were used, 0.5 and 50%/min. After the tests were conducted, the deformation substructures were characterized by transmission electron microscopy (TEM). Although the cyclic work has just recently begun, the results to-date include some unexpected deformation behavior. If these trends are also evident in the cyclic testing, they will have strong implications for the applicability of current constitutive models.

Figure 1 is a summary of the yield strength data. It can be seen that below 760°C, the strength is independent of temperature and strain rate. Above 760°C, the strength becomes of function of temperature and strain rate, due to the fact that the plastic deformation in this regime is thermally activated. Frequently, thermally activated processes can be characterized very well by an Arrhenius-type relationship of the form:

$$\sigma = A(\exp[Q/RT])$$

where Q = Activation energy
 T = Temperature
 R = Gas constant
 A = Constant

Figure 2 is a plot of the data in this form. It is seen that the data falls naturally into three temperature regimes. Analysis of the deformation substructures resulted in the same three regimes, and the boundaries of the regimes were the same. Reference (2) should be consulted for details, but a short summary is presented below.

At low temperatures, when the strength was independent of temperature, slip was very crystallographic. Deformation occurred by shearing of the γ' on {111} planes. In this regime, the crystallographic models which add plastic shear strains on different systems (both inside and outside the γ') would appear to be generally applicable.

At high temperatures, where the activation energy for yielding was independent of strain rate, slip was extremely homogeneous. Additionally, the γ' was not sheared during deformation. The particles were by-passed by diffusion-controlled climb. In this regime, the γ' was not sheared, so the crystallographic models which consider cube slip within the precipitates would not be applicable.

Intermediate temperatures resulted in transitional behavior.

It must be stressed that the above discussion is limited to deformation during the initial stages of a tensile test, and only the {001} orientation was tested. Later in the program, cyclic and off-axis studies will be conducted to see if the conclusions are more general.

References

1. D. P. Pope and S. S. Ezz: Int'l. Metals Review, 1984, vol. 29, p. 136.
2. W. W. Milligan: NASA CR-175100, 1986.

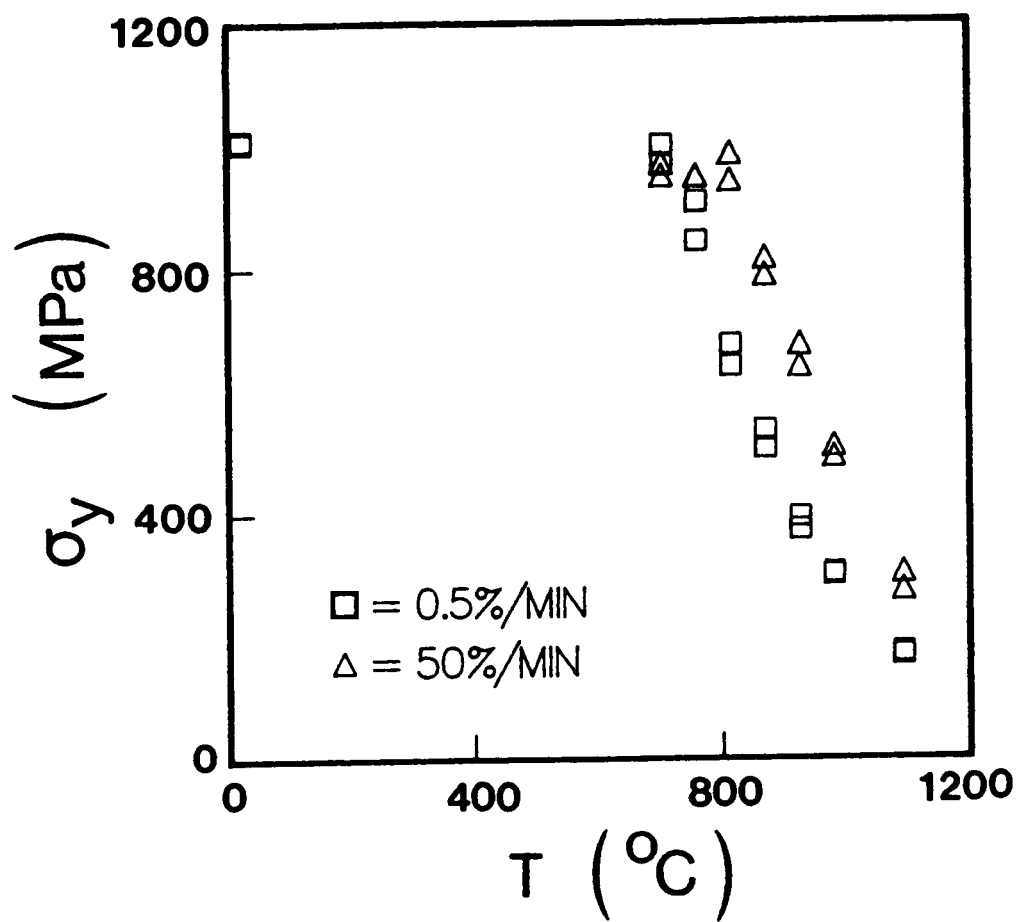


Figure 1. Yield strength at 0.05% offset vs. temperature.

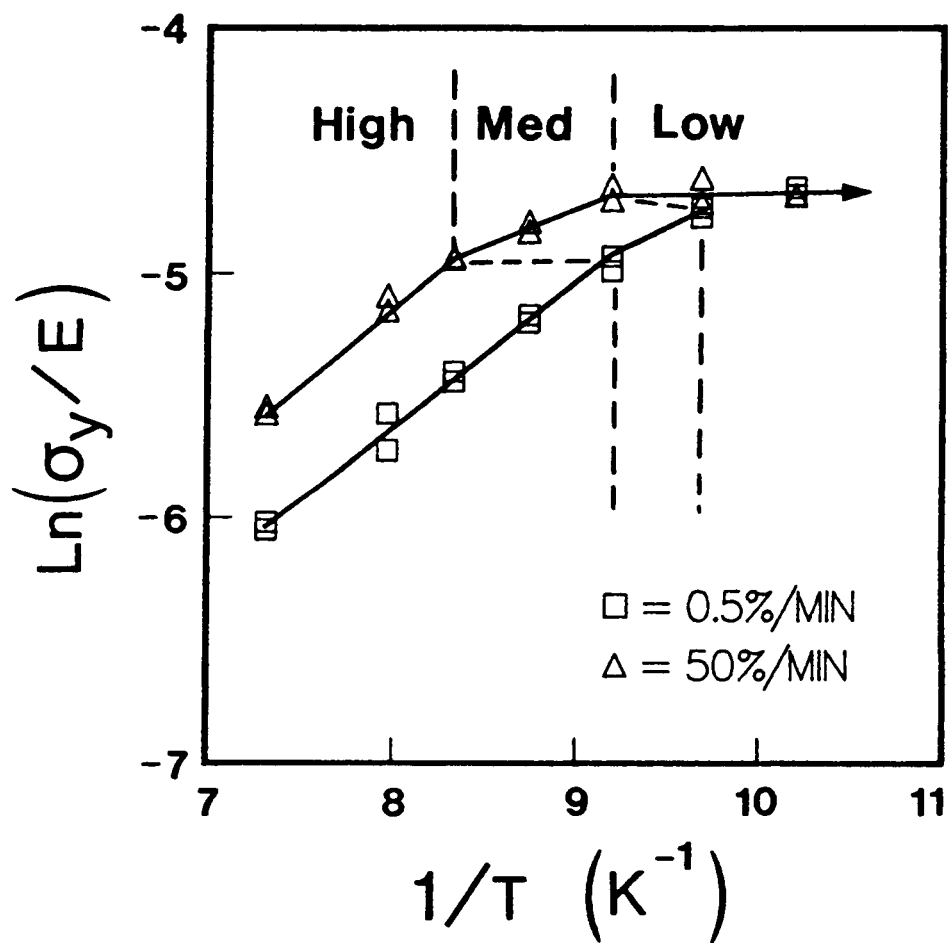


Figure 2. Arrhenius-type representation of the yield strength data.